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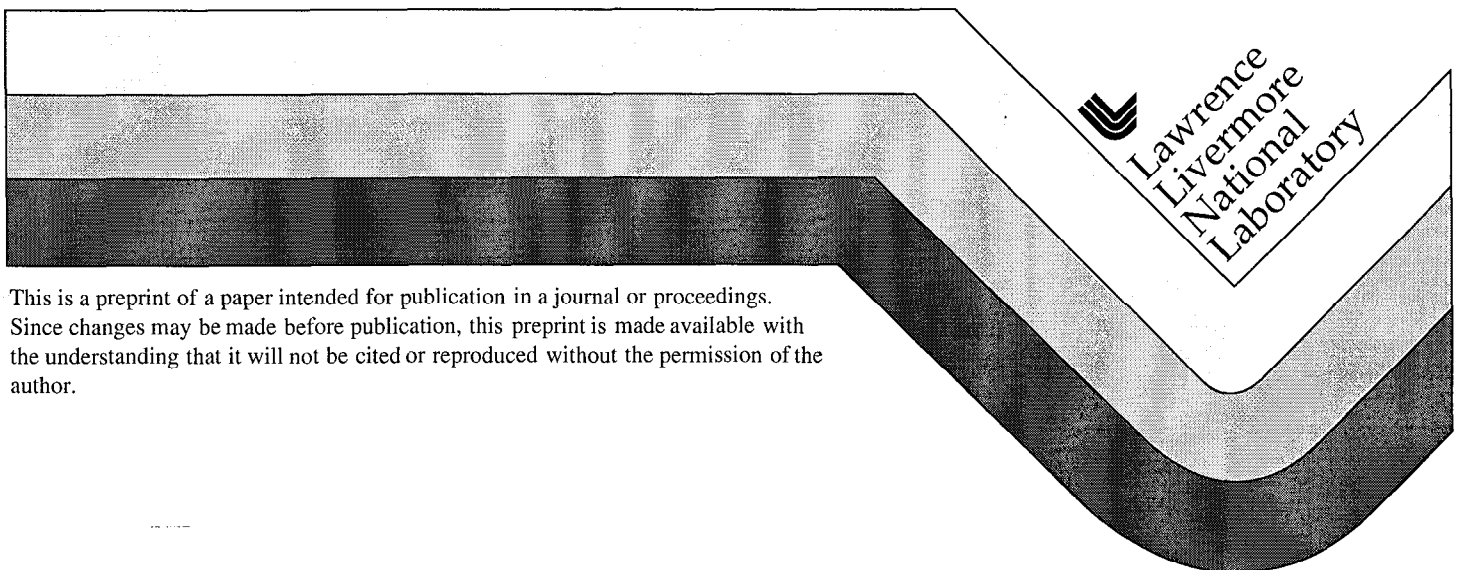
PREPRINT

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Three dimensional Monte-Carlo modeling of laser-tissue interaction

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ABSTRACT

A full three dimensional Monte-Carlo program was developed for analysis of the laser-tissue interactions. This project was performed as a part of the LATIS3D (3-D Laser-TISsue interaction) project. The accuracy was verified against results from a public domain two dimensional axisymmetric program. The code was used for simulation of light transport in simplified human knee geometry. Using the real human knee meshes which will be extracted from MRI images in the near future, a full analysis of dosimetry and surgical strategies for photodynamic therapy of rheumatoid arthritis will be followed.

1. INTRODUCTION

Recently LLNL launched a project called LATIS3D¹ (three dimensional LAser-TISsue interaction). This project includes development of individual three dimensional calculation packages of light transport, heat transfer, material response, and hydrodynamic process. Ultimately these separate packages will be interactively coupled to do complete nonlinear simulation of complex laser-tissue interactions. As a part of the LATIS3D packages, a full stand-alone version of 3-D Monte-Carlo program was developed.

The code was written in fully object-oriented C++ language that allows easier maintenance and modification and easier integration with other codes. It was also designed so that unstructured meshes can be used, thus fewer zones will be required and complex geometries can be handled with relative ease.

The 3-D Monte-Carlo code was designed so that the tissue parameters could be incorporated. First of all, the Henyey-Greenstein scattering function was used to simulate the scattering by tissue particles^{2,3}. Secondly, each zone can possess different optical properties so that mixtures of various tissues can be analyzed. Non-uniform refractive indices can be assigned to each zone, thus, Fresnel reflection/transmission can be calculated every time each photon passes the boundary between adjacent zones. The probability function of Fresnel reflection and transmission is given by Fresnel equation. Thirdly, surface irradiance source and internal isotropic source can be used depending on the laser delivery types.

This code can be used for a variety of medical applications for parameter optimization and surgical strategy development. One of the fields that are of interest is to calculate the light distribution in human knee for photodynamic therapy of rheumatoid arthritis. The knee is composed of many different types of tissues organized in a very complex way. These tissues include ligament, fat, bone, cartilage, muscle, synovium, and synovial fluids. It is therefore extremely hard to predict the light distribution which is a key issue for success of the photodynamic therapy. There is an ongoing effort between LLNL and UC-Davis to generate complex unstructured meshes out of MRI images of human knee. This project is not complete at this stage and this paper presents preliminary results calculated using highly simplified knee models.

Two issues are discussed in this paper: (1) the effect of the boundary structure for light distribution at soft-hard tissue junction, (2) the effect of diseased synovial membrane on light penetration.

2. CODE VERIFICATION

A well-verified three-dimensional program that can be used for verification of our code was not available at this stage. Instead, a widely accepted public domain two-dimensional Monte-Carlo program was used against the results of new 3-D code [4],[5]. Two simple tests were done and the results are shown in Fig. 1. Fig. 1(a) shows the axial light intensity variations calculated using the two codes assuming uniform material properties. In Fig. 1(b), a two layer geometry with different optical properties and refractive indices was used for comparison. The second layer possesses refractive index of 1 (air) but non-zero optical properties which are not physically possible to obtain. These numbers were used just to see if the new code can simulate the sudden drop of intensities at the material junction. The results were excellent for both cases as shown in the figures.

3. RESULTS AND DISCUSSION

Conventional simple mesh generators generate structured meshes using uniformly sized boxes, prisms, etc. When material boundaries do not coincide with the zone boundaries, the structured meshes cannot represent the exact shape of the boundaries. Instead, zigzagged, step boundaries will be formed between two materials as shown in Fig. 2(a). This might be an issue in light transport calculation with multiple materials with various refractive indices since the Fresnel reflection/transmission strongly depends on the incident beam angle on the boundary surfaces between two materials. This argument is valid when the material boundaries are placed near the source and the scattering patterns are not completely diffuse. Optical modeling using human knee meshes inevitably requires calculation of the light distribution around the soft/hard tissue junction or clear

synovial fluid/hard tissue junction. Since it is well known that the refractive indices of soft and hard tissues are different⁴, the boundary geometries should be treated carefully.

To test the importance of boundary geometries, simple calculations were performed using two distinct boundaries. Fig. 2(a) shows the step boundary between the synovial fluid and bone tissue and Fig. 2(b) shows the tilted (smooth) boundary. It was assumed that the beam is incident vertically upon the surface and the refractive indices were 1.6 and 1.3 for bone (or cartilage) and fluid respectively.

The normal direction from the tilted boundary is at 45° angle from incident beam while the normal from the step boundary has 0° angle. The calculated light distributions along the axial direction at radial position as shown with a dotted line in figures were compared and the error was calculated as:

$$Error = \frac{Step\ Boundary - Tilted\ Boundary}{Step\ Boundary} \times 100(\%)$$

The results show that when the boundary geometry was not considered properly the error can be as high as 25% as shown in Fig. 3(c). Since more light energy is reflected to the synovial fluid with tilted boundary, less energy was deposited to the bone tissue. This implies that using unstructured meshes can reduce the possible artifact caused by using structured and non-realistic mesh boundaries.

The second set of studies focused on the simulation of light distribution using simplified knee meshes for both normal and diseased cases. Fig. 4 shows the simplified knee meshes which are composed of various sized boxes of skin, muscle, synovial membrane, synovial fluid, bone, meniscus and cartilage. Typically, the synovial membrane of the diseased knee becomes swollen and contains more blood. Hence, the optical properties (absorption or scattering coefficients) of the diseased synovial membrane were assumed to change from 0.1 cm⁻¹ to 0.5 cm⁻¹ and the thickness changes from 1 mm to 3 mm. The wavelength was assumed to be 700 nm and the optical properties were chosen for this wavelength.

Fig. 5. shows the light distributions on the cross-sections of the knee model shown in Fig. 4. The normal and diseased tissue models are displayed in top and bottom rows respectively. Figs. 5 were drawn assuming the light sources were placed at the skin/muscle junction, and at muscle/synovial membrane junction respectively. This preliminary study shows that the noninvasive external light delivery is significantly blocked due to highly absorbing muscle layers. It may be desirable to deliver light energy directly to the synovial membrane using fibers. Also, as expected obviously, the diseased synovial membrane prevents light energy from penetrating further.

These preliminary studies were performed using over-simplified tissue geometries and some optical parameters were assumed for various types of tissues. Further

investigations will focus on obtaining the real three dimensional human knee meshes from MRI images and on measurement of optical properties for those tissues which optical properties are not known yet.

4. CONCLUSION

A full three dimensional Monte-Carlo code was developed for analysis of laser-tissue interactions. Some preliminary results obtained using this code showed that the tissue boundary structure might influence the calculation of light distribution in case structured meshes are used. A simple calculation was also performed using simplified knee meshes showing effects of various types of tissue layers.

ACKNOWLEDGMENTS

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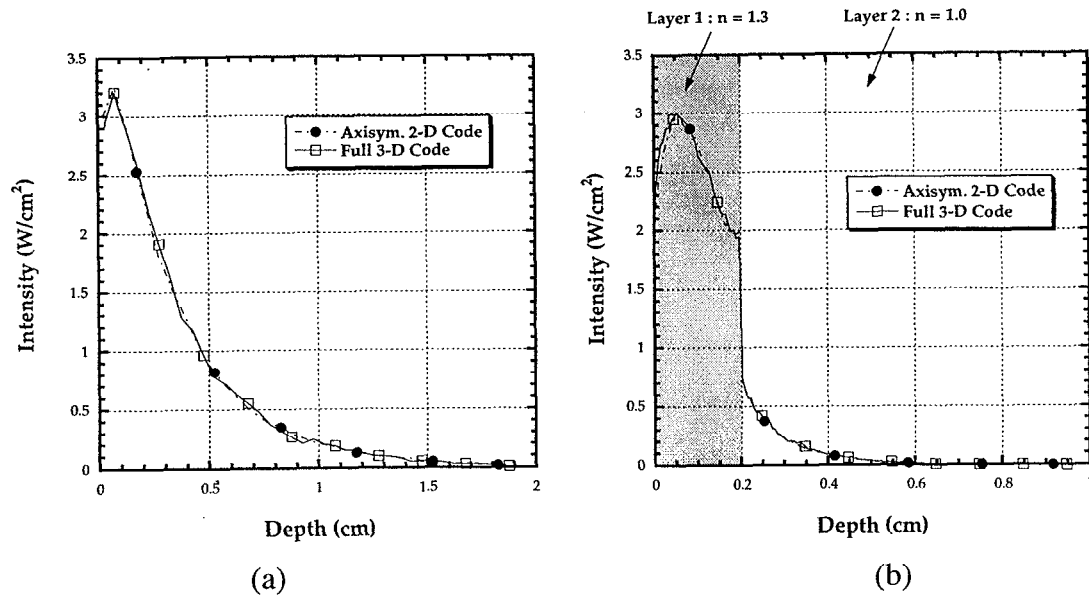


Fig. 1. Results of 2-D axisymmetric code and 3-D code overlay nicely throughout the material depth. Calculations were done using (a) 1 layer and (b) two layers.

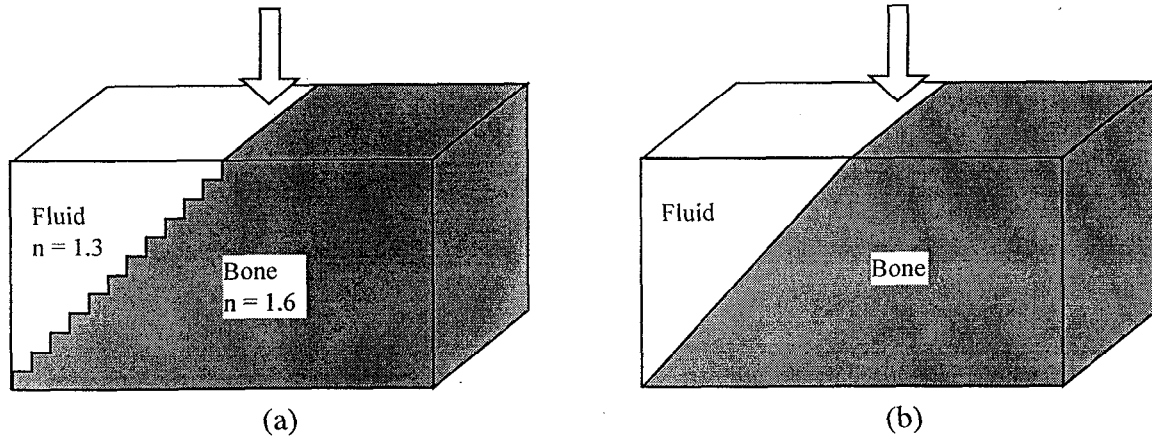


Fig. 2. Shape of the boundaries for (a) structured and (b) unstructured meshes. The unstructured meshes can simulate the shape of the boundaries freely.

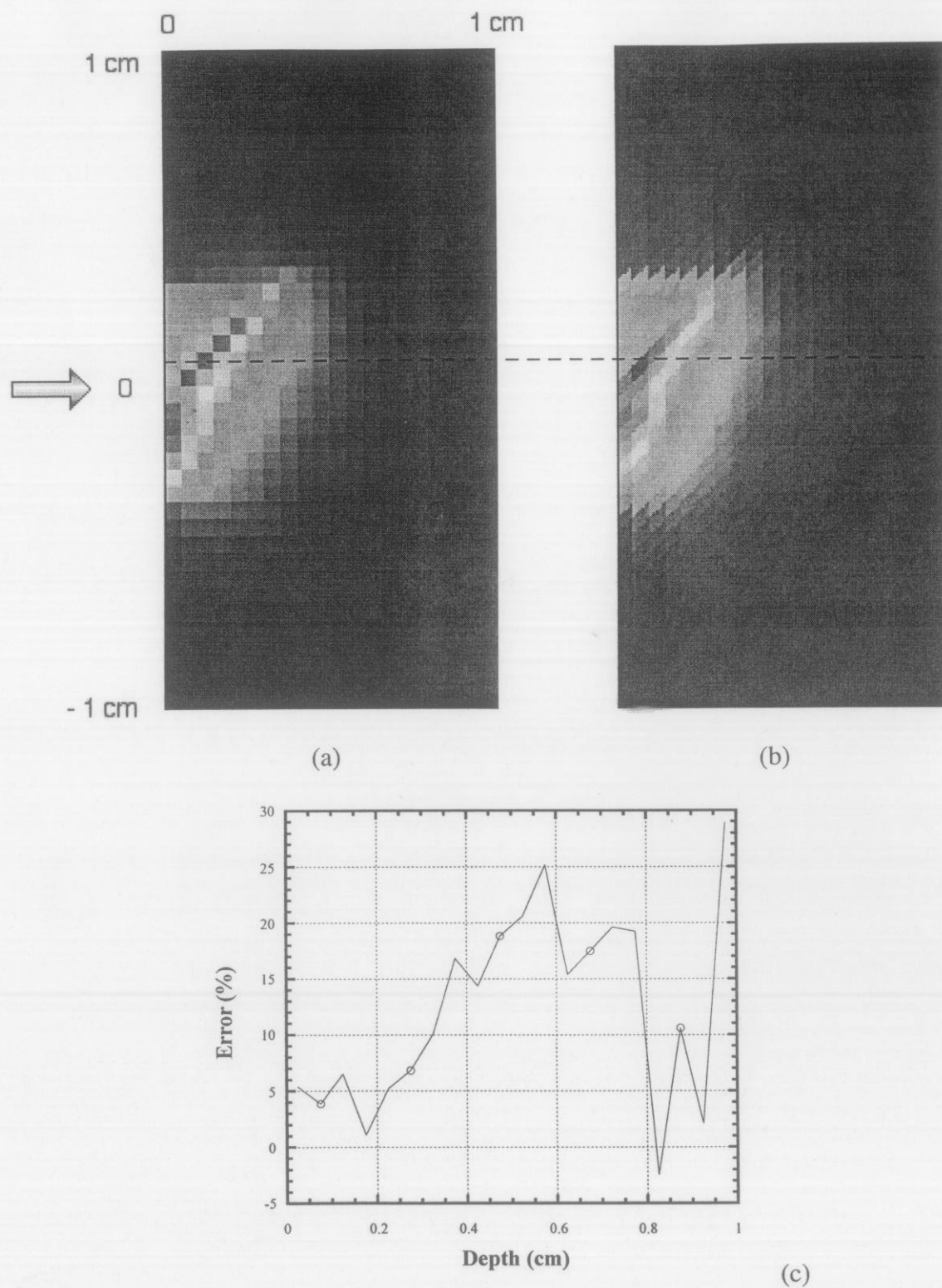


Fig. 3. Cross-sectional views of the two different boundaries: (a) step boundary, (b) tilted boundary. The error is shown in (c) as a function of depth.

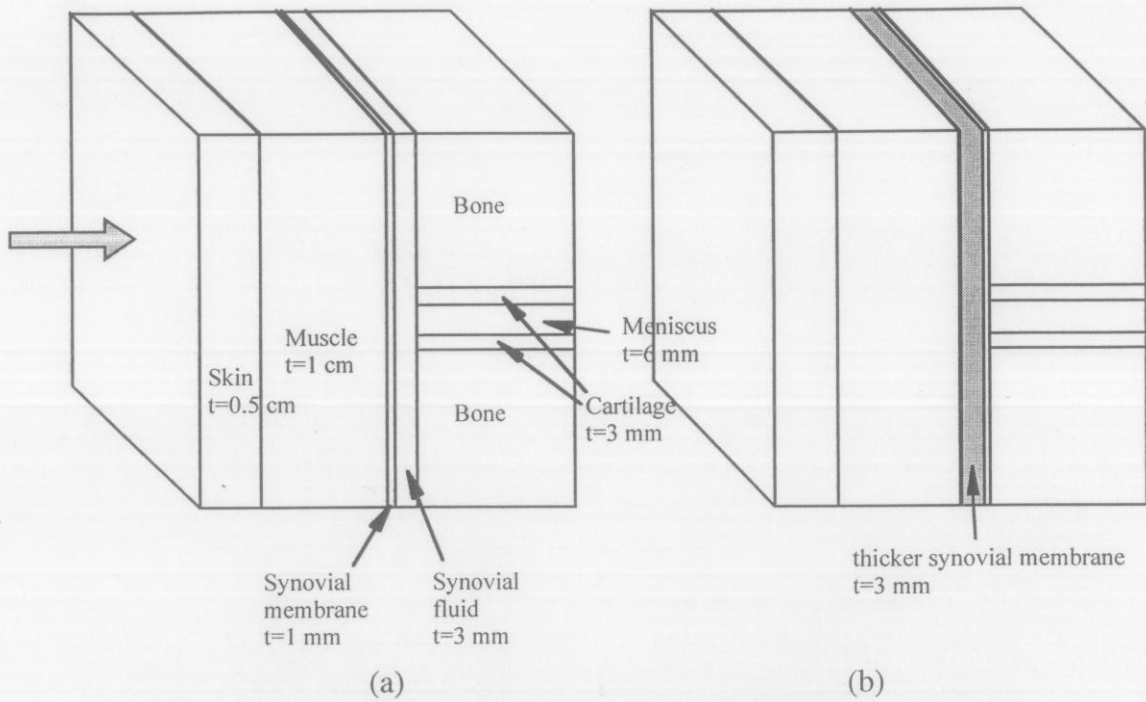


Fig. 4. Simplified knee model for (a) intact and (b) diseased knee.

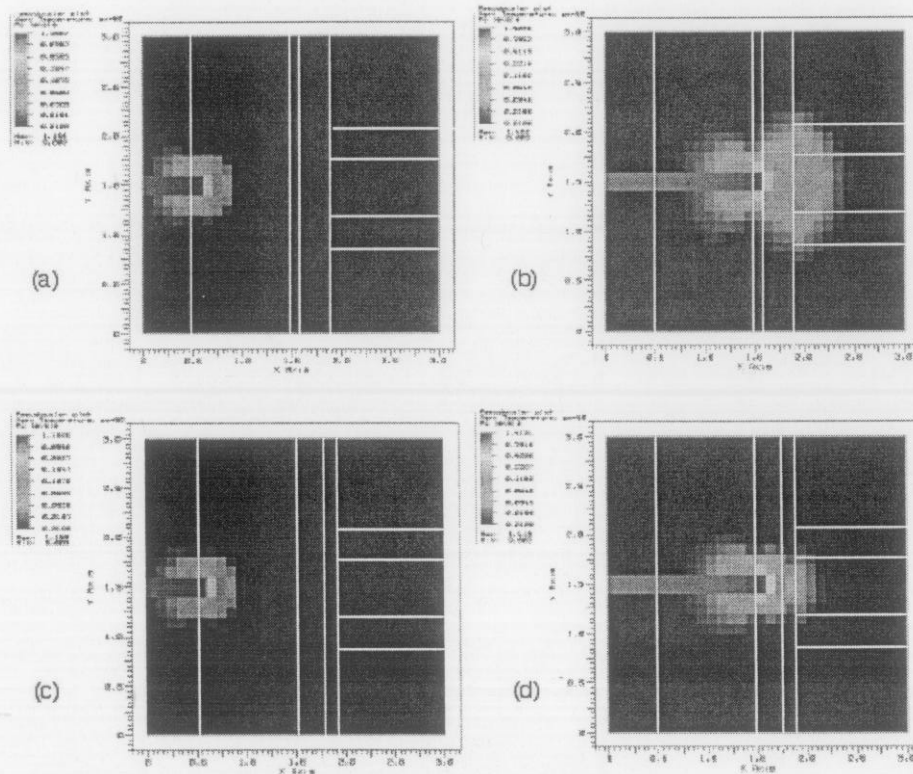


Fig. 5. Simulation results using simplified knee meshes. (a) and (b) intact knee mesh with different source locations. (c) and (d) diseased knee mesh with different source locations.